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LOW-COST COMPOSITE BLADES FOR THE MOD-OA WIND TURBINES

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ABSTRACT

This paper describes the Low-Cost Composite Blade Program, carried out by Structural Composites Industries, Inc. (SCI) under contract to NASA-Lewis Research Center (NASA), (funded by the Department of Energy), involving design, evaluation and fabrication of a pair of composite rotor blades for the MOD-OA wind turbine. The objectives of the program were to identify low cost approaches to the design and fabrication of blades for a two-bladed 200 kW wind turbine and to assess the applicability of the techniques to larger and smaller blades.

SUMMARY

Rotor blades represent a substantial portion of the cost of intermediate to large-size wind turbines. Therefore, low-cost blades are needed to improve the overall cost effectiveness of these systems.

In Phase I of the Low-Cost Composite Blade Program, several blade designs were developed to the point where reasonably accurate estimates could be made of the structural properties and costs of tooling and fabrication. The most cost-effective design was selected for detailed design in Phase II. Structural analysis of the selected design was performed, with assistance from NASA in some of the more specialized techniques (e.g., flutter analysis). Subelement and subscale specimens were fabricated in Phase I for testing by both SCI and NASA. These tests were used to: confirm the physical and mechanical properties of the blade materials; develop and evaluate certain blade fabrication techniques and processes; confirm the structural adequacy of the root end joint design.

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In Phase II, blade tooling was designed and fabricated. Two complete blades and a partial blade for tool tryout were built. A patent-pending 100 ft long "ring-winder" machine, designed and built with private funding, was contributed by SCI.

The patented TFT process, developed by SCI and used to fabricate the spar for the DOE/NASA 150 ft composite blade (Ref. 1) was used, in this program, to wind the entire blade. This process allows rapid winding of an axially oriented composite onto a tapered mandrel, with tapered wall thickness. The TFT process thus is uniquely suited to low cost composite blade and spar fabrication.

The ring winder/TFT process combination was used for the first time on this program. This approach allows the blade to be wound on a stationary mandrel, an improvement which alleviates some of the tooling and process problems encountered on previous composite blade programs. The stationary mandrel, with it's chordline vertical, is in it's stiffest orientation, so deflection is small and constant. The absence of cyclic stresses reduces the chance of premature mandrel failure and assures long tooling life. In addition, doubts about the effect of constant mandrel flexing on the wet or partially cured composite are eliminated.

The low-cost blade adapts to the MOD-OA hub via a bolted circular metal flange. This flange is in an area of maximum steady and cyclic bending moments and shear forces. One challenge in composite blade design is to incorporate such a flange into the composite structure in a manner that facilitates low-cost fabrication while assuring adequate structural margins in this critical area.

In preparation for the low-cost blade program, SCI developed, using private funds, a patented metal hub fitting design which meets the goals stated. The flanged metal fitting is designed to fit over the winding mandrel. It is provided with angular grooves into which the TFT composite is pulled, by tensioned hoop windings, for a mechanical lock. The fitting also contains a bonded transition area where the stiffness gradually transitions from composite to steel.

For redundancy, either the bonded or mechanical joint can accept the full load on the hub. This joint has been thoroughly tested by NASA on two half-scale spars provided during Phase I.

The use of an all-wound blade structure with a wound-in hub fitting, painted and cured in the winding machine, means that the blade is substantially complete when it leaves the winding area. Only minor trimming and assembly operations remain. This approach, with the improvements listed in the conclusions and recommendations section, promises to provide truly low cost composite wind turbine blades in a production environment.

The two 60 ft blades were transported to NASA-LeRC in Cleveland, Ohio from SCI in Azusa, California using one standard extendible 60 ft truck. No crates or special handling fixtures were needed.

The projected cost of production blades in 1978 dollars, built in 100 unit lots, is $11,745 each or $4.12/lb. for a 2852 lb blade. This is well within the NASA guidelines.

BLADE DESCRIPTION

The final blade configuration, which was designed and analyzed to meet all the NASA design requirements, is shown in the planform sketch of Figure 1. The blade consists of a TFT glass-epoxy airfoil structure filament wound onto a steel root end fitting. The fitting is, in turn, bolted to a conical steel adapter section to provide for mounting attachment to the NASA hub.

A typical cross section of the blade is shown in Figure 2. The blade comprises a 3-cell design configuration containing a leading edge D-spar section followed by a foamed afterbody and a foamed trailing edge cell. The D-spar and afterbody cells constitute the primary structural cells of the blade.

ROOT END FITTING

The steel root end fitting is shown schematically in Figure 3. The fitting contains two recessed groove areas to allow mechanical locking of the axial TFT filament wound composite onto the fitting. The locking is achieved by a series of 90° hoop wraps at the groove locations. This SCI patented design approach improves the structural reliability of the joint in the event of adhesive bond failure at the TFT-steel interface.

The gradual taper of the fitting at the outboard edge is designed for smooth load transfer between the spar and the fitting. The shallow conical angle of 4° also facilitates blade manufacturing during the filament winding process. The fitting is circular in cross section to mate to the hub adapter flange and to allow low cost fabrication by lathe turning of a ring forging. Three Huck-bolts are spaced radially around the circumference to positively prevent blade rotation in the event of adhesive bond failure.

HUB ADAPTER

The steel hub adapter for transferring blade loads to the NASA hub is shown schematically in Figure 4. The adapter configuration and in particular the overall length was designed to minimize kick load effects at both the blade hub fitting and MOD-OA hub mounting interfaces. The bolted joint configuration at the hub/fitting interface is designed to facilitate field installation of the blade. The internal bolting surface of the adapter at the hub/adapter interface requires assembly of the adapter to the hub prior to blade attachment to the adapter.

BALANCING, ICE DETECTION, LIGHTNING PROTECTION

BALANCING PROVISIONS

Forward and aft tubes are provided at root and tip for chordwise and spanwise balancing and tuning. A large tube is provided near the c.g. for matching the weights of blades in a pair. Weight is added by injecting a non-metallic high density filled room temperature curing resin into these tubes.

ICE DETECTION

The NASA-furnished ice detector is mounted into a metal recessed flange which is wound into the trailing edge. The wiring conduit is routed along the aft end of the first afterbody wrap. This arrangement allows installation of the detector and wiring without cutting holes in any of the primary blade structure.

LIGHTNING PROTECTION

Since the composite blade is non-conductive, it is necessary to provide a conductive path along the blade surface from the aluminum tip cap to the hub fitting to ground any lightning strikes. A 6-in. wide by 0.004-in. thick aluminum foil strip is bonded along the trailing edge and routed to the hub.

MATERIALS OF CONSTRUCTION

The principal reinforcement is E-glass continuous filament roving which has been woven into transeverse filament tape (TFT), bias filament tape (BFT) and longitudinal filament tape (LFT). TFT has the primary filaments transverse to the axis of the tape. When this tape is wound circumferentially around the blade, it deposits the transverse filaments at approximately 0^{o} to the spanwise axis. In an analogous manner, BFT is used to provide $\pm 45^{o}$ reinforcement. LFT is used to produce 90^{o} reinforcement for chordwise strength. The resin matrix used is the same as that used on the 150 ft composite blade. It is an amine-cured epoxy containing a reactive dilutent.

STRUCTURAL ANALYSIS AND BLADE PROPERTIES

APPROACH

The analysis utilized both computerized and hand calculations to evaluate the structural integrity of the blade. Computer math models of the blade, hub joint and mandrel were developed and analyzed for stress response and internal load distribution. Hand calculations were then performed to evaluate critical design components based on the internal load distributions. Minimum margins of safety computed for major structural components of the blade are summarized in Table 1.

ALLOWABLES

Strength

The strength allowables used in the analysis are the minimum yield and ultimate strength values known for the materials listed. In the case of the composite TFT and hoop (LFT) material and the adhesive, the yield strength was taken to be 80% of the static ultimate strength of the material. For the adhesive a knockdown factor of 0.75 was applied to the average ultimate strength of the adhesive as reported in the literature for bonded scarf joints to develop the design ultimate strength. In the case of TFT composite spar material, the strength data were derived on the basis of maximum lamina strain theory using a laminate analysis computer program. The resultant failure envelope for the spar material is shown in Figure 5.

Buckling

The allowable buckling stresses for the blade were computed according to the expression

$$\sigma_{\text{Calc.}} = 0.314 \left[\frac{2-(b/a)^2}{(b/a)^2} \right]^{0.12} \bullet \frac{E_e}{1-\nu_{12}\ \nu_{21}} \left(\frac{t}{\bar{r}} \right) \qquad (1)$$

where, (b/a) = Blade Aspect Ratio

T/F = Thickness to Critical Radius of Curvature Ratio

ν = Poisson's Ratio

$E_e = \frac{1}{2}\sqrt{E_{11}E_{22}} + \frac{1}{2}\ \nu_{12}\ E_{22} + \left(1-\nu_{12}\ \nu_{21}\right) G_{12}$

A knockdown factor of 0.45 was applied to Equation (1) to provide design allowable buckling stresses.

Fatigue

The fatigue allowable for the metal is the minimum endurance limit for notched fatigue strength taken from the literature. This value has been experimentally characterized over a large specimen population and can confidently be used in the blade application.

The fatigue allowables for the TFT composite blade material were determined from the expression

$$S_{MAX} = \frac{6.20}{1-\ .690R} \qquad (2)$$

S_{MAX} = Allowable Maximum Stress

$R = \sigma_{MIN}/\ \sigma_{MAX}$

σ_{MIN} = Applied Minimum Stress

σ_{MAX} = Applied Maximum Stress

Equation (2) is based on the regression analysis of data from 150 ft spar tests at NASA.

The shear fatigue strength of the adhesive is based on a review of experimental fatigue data on adhesives given in the literature. The value of 1280 psi represents approximately 40% of the yield shear strength of the adhesive. Fatigue endurance limits of this magnitude appear characteristic of single lap shear joint behavior under cyclic loading.

BLADE PROPERTIES

Stiffness Distributions

The flexural stiffness distributions of the blade in the flatwise and edgewise directions are shown in Figures 6 and 7, respectively.

Weight, Center of Gravity and Mass Moment of Inertia

The total predicted weight of the final blade design for structural analysis is 2582 lbs. A breakdown of this weight is shown in Table 2.

The spanwise distribution of this predicted weight is shown in Figure 8. The center of gravity of the blade is located at STA (r/R) = .302. The predicted gravity bending moment of the blade about STA 40 in. is 44,400 ft/lbs.

COMPARISON TO NASA SPECIFICATIONS

Table 3 summarizes the actual versus NASA specified characteristics of the final SCI low-cost blade design. The only parameter which is out of the specified range is the chordwise center of gravity, which is 38% from the leading edge, against a specified maximum of 32%. NASA analyzed the SCI design for flutter and pitch control forces and determined that the 38% location was acceptable for this particular design.

MANUFACTURING CONSIDERATIONS

In this section we will discuss manufacturing considerations for the final SCI design.

FABRICATION PROCEDURES

Figure 9 is an overall flow diagram for the SCI blade.

Preparation

The first major step is the process used to vacuum-impregnate the TFT material. The dry tape is unwound into baskets which are placed into a tank for vacuum impregnation. The wet impregnated material is then rewound onto spools which fit the ring winder. The BFT and LFT did not require the vacuum impregnation step, but were wound from the supply spool through a resin bath, and directly onto the ring winder spools.

Other preparation included precutting of the foam cores and the various plies of the web doubler layup, surface preparation and application of release agent to the mandrel.

Blade Winding

Figure 10 shows the overall winding arrangement for the blades. The water-filled headstock and tailstock support the D-spar mandrel in a fixed position while the traversing ring winder wraps the tape to form the composite. The foam cores are added in succession to form the afterbody and trailing edge.

Curing and Extraction

The cure oven is rolled over the wound blade from its parked position at the headstock end. A 200 kW electric hot air blower is used to heat the oven.

For mandrel extraction, the tailstock is removed. Four 50 ton hydraulic jacks, driven by a common hydraulic power supply, push against the bucking ring to free the blade from the mandrel. The freed blade, supported by two cranes, is then moved clear of the mandrel while temporary blocks are positioned under the mandrel to support it until the tailstock is replaced.

Final Finishing and Assembly

The finished blade is painted in the winding machine prior to final cure. The lightning protection strip is applied prior to painting. After extraction, balancing tubes, D-spar rib, ice detector and tip cap are installed to complete the blade.

QUALITY ASSURANCE

The overall quality assurance flow chart for the low-cost composite blade is presented in Figure 11. Receiving inspection, in-process inspection and final inspection steps are included.

TOOLING DESIGN AND FABRICATION

Tooling designed for the low-cost composite blade included the winding mandrel and its supports, the tape impregnation equipment and jigs, fixtures and templates for alignment of the blade components during fabrication. The most critical item of tooling was the D-spar mandrel, which is the "backbone" upon which the blade is built.

Structural analysis showed the maximum predicted deflection of the mandrel is less than 1 inch. The maximum skin stress was found to be approximately 5400 psi which is well below the yield stress of the AISI 1020 steel material.

HANDLING AND SHIPPING

The blades were shipped on a 60 ft extendible bed truck. The root end fitting was used to support the heavy root end and to take axial acceleration loads. The blades were lifted with a pair of straps centered on the CG.

APPLICABILITY TO OTHER SIZES (15 - 200 ft)

No constraint was found in applicability of the LCCB design and fabrication techniques to other sizes. Similar blades have been proposed, studied, designed or built on several other programs in lengths from 15.5 to 250 ft. The filament winding process is not limited to any particular size. (SCI has filament wound large structures such as a railroad car body and a 22½ ft dia x 60 ft long rocket motor case). It is only necessary to provide a large enough winding machine and mandrel(s). Since the composite is being fabricated by the winding process, there is no limitation such as size of available plates or sheets of material. The rovings and tapes used in filament winding are continuous and of practically infinite length.

In the smaller size blades, such as the SCI blades designed for the 4 kW SWECS program, it might be cost-effective to mold the outside surface to final contour after winding. This method is used on helicopter rotor blades. It results in a better contour and surface finish, a denser laminate, and fast cure cycle.

RESULTS OF BLADE INSPECTION

The blades were inspected for dimensional accuracy, weight and balance, and finish and appearance.

DIMENSIONAL INSPECTION

Measurements were taken of the upper and lower airfoil contours. The total points measured were 96 per blade. The measurements utilized sheet metal airfoil contour templates made from the airfoil mylars.

The results show a mean error for all measurements of -.085 in. This resulted from a general reduction in composite wall thicknesses and foam dimensions due to the vacuum bags used to reduce resin and void content, and the shrinkage of the foam during cure.

The overall accuracy and fairness of the blade contour was adversely affected by the vacuum bagging which tended to pull the wet windings into any low spot in the mandrels, whereas the windings normally tend to bridge and smooth out these places. The effect was especially pronounced in the fairing material used to smooth the transition from foam core to D-spar or first afterbody.

The material was changed from syntactic foam to low density polyurethane foam to save about 100 lbs per blade. This foam-in-place material tended to shrink and soften during blade cure, leaving a spanwise indentation or trough in the outer blade surface.

Another problem encountered was local denting of the trailing edge by winding tension collapsing the foam core.

FINISH AND APPEARANCE

The exterior surface finish of filament wound composites is a "natural" finish with some "grain" from the windings. The TFT process uses final passes of 90° hoop windings or LFT to compact the composite and give a lay of the "grain" in the chordwise direction.

The surface finish achieved is estimated to be NASA standard roughness. Appearance, on close up viewing, leaves room for improvement due to the rough finish and the irregularities discussed under "Dimensional Inspection". These problems should not affect blade performance and can be improved on production blades by learning, lower cure temperatures, elimination of vacuum bagging, and the use of "foam in place" cores.

WEIGHT AND BALANCE

Table 2 shows an actual versus predicted weight summary of the blades. Within the accuracy of the scale used, the weights of the finished blades, prior to balancing, were identical at 2180 lbs (not including hub adapter). The as built center of gravity was also quite close, within 1/8 inch. Both parameters were well within the NASA-specified tolerances of ± 2% (about 50 lbs blade to blade) on weight and ± one inch on spanwise c.g. Chordwise c.g. was not checked. Total weight was 10% less than estimated, mostly due to the compaction achieved by vacuum bagging. These results are encouraging, promising good reproducibility from blade to blade.

COST AND WEIGHT ANALYSIS

WEIGHT SUMMARY

The projected weights for the LCCB are listed in Table 3. The 2852 lb projected weight is well below the 3000 lb absolute limit for MOD-OA.

PRODUCTION COSTS

In Table 4 the costs for quantities of 2 through 1000 production blades are estimated. The assumptions made for these estimates include (1) the use of foam in place cores for the afterbody and trailing edge, (2) a web doubler wound into the D-spar, (3) continuous winding with only one cure cycle and no vacuum bags or peel ply. This modified sequence reduces labor substantially since the cutting, bonding and fairing of the foam cores and the hand layup and positioning of the web doublers on the prototype blades were very labor-intensive, as were the multiple cures, vacuum bags and peel plies.

COMPARISON TO NASA SPECIFICATION

Figure 12 shows the NASA weight cost envelope with the production version of the SCI LCCB plotted. At $11,745 and 2,852 lb, it is well within the envelope.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

- This program demonstrated a unique and potentially low cost approach to the design and fabrication of blades for a two-bladed 200 kW wind turbine.
- No technical limitations were found which would prevent the application of the same techniques to blades from 15 to 200 feet in length.
- The ring winder and TFT process are practical approaches to fabrication of complete large composite multi-cell blades, and eliminate the problems of mandrel deflection, while facilitating the wrapping of an axially oriented composite, with tapering wall thicknesses.

- The mechanically locked hub flange design is structurally adequate for use in large composite wind turbine blades.

RECOMMENDATIONS

The prototype low-cost composite blades were well within the MOD-OA weight and gravity moment restrictions, but were costly to fabricate. Future wind turbines should have hub designs which are coordinated with the blade design to give the lowest possible cost of energy. The following recommended changes in the present design and process could then be implemented:

- Two cell design with D-spar as the primary load-carrying element.
- Larger hub diameter to allow extraction of larger mandrel without using a metal root end adapter.
- Aluminum or mild steel hub fitting for lower cost.
- Polyester resin for lower raw material and processing cost.
- Continuous winding process without costly vacuum bag, peel ply and gel between winding steps.
- Hollow afterbody wound on extractable mandrel. (If foam core must be used in afterbody, then foam in place in a mold).
- Consider use of modified airfoil with blunt trailing edge.

NOTICE

The blades discussed in this report were manufactured under one or more of the following U.S. Patents issued to Structural Composites Industries, Inc., Azusa, California:

4,260,332
4,264,278
4,273,601

And other patents pending.

REFERENCES

1. Kaman Aerospace Company, "Design, Fabrication, Test and Evaluation of a Prototype 150-Foot Long Composite Wind Turbine Blade", NASA CR-159775, September 1979.

TABLE 1
CRITICAL LOAD CONDITIONS AND MARGINS OF SAFETY

Component	Critical Load Condition	Failure Mode	M. S.
Blade Tip Impact with Tower	Shutdown	Deflection	0.06
D-Spar	Shutdown	Tensile	1.13
D-Spar	Survival Wind	Buckling	0.14
D-Spar	Operation	Flatwise Fatigue	0.38
D-Spar	Operation	Edgewise Fatigue	1.67
D-Spar	Operation	Combined Fatigue	0.17
Trailing Edge	Survival Wind	Buckling	0.46
Hub Joint Fitting	Operation	Tensile	0.14
Hub Joint Spar	Operation	Fatigue	0.17
Hub Joint Adhesive	Operation	Fatigue	0.25
Hub Joint Hoops	Operation	Fatigue	1.32
Hub Adapter	Operation	Tensile	1.93
Root End Closure	Survival	Buckling	1.83
Ribs	Operation	Fatigue	2.35

TABLE 2
WEIGHT COMPARISONS

MATERIAL	TOTAL BLADE WEIGHT (LBS)		
	FINAL DESIGN	AFTER TOOL TRYOUT	ACTUAL BLADE
STEEL HUB FITTING	265	273	
COMPOSITE	1742	1808	
2-LB. FOAM	67	58	
4-LB. FOAM	87	93	
FOAM FILLER	118	21	
ADDITIONAL HARDWARE, PAINT, MISC.	200	105	
TOTAL	2479	2358	2180
HUB ADAPTER	373	373	395
GRAND TOTAL	2852	2731	2575

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TABLE 3
COMPARISON TO NASA SPECIFICATIONS

	SPECIFICATION	ACTUAL
AIRFOIL	NASA - 230XX	230XX
TWIST	10° MAXIMUM	10°
MAXIMUM THICKNESS, ROOT	40%	30% (.25R)
MAXIMUM THICKNESS, TIP	18%	12%
HUB FLANGE	NASA DWG. CD. 758866 AT STATION 31.75 INCH	SAME (WITH ADAPTER)
PLANFORM	STRAIGHT, STEPPED OR TAPERED	TAPERED
ROOT CUTOUT	MAXIMUM 25%	12-1/2%
LENGTH	60 FT. HUB FLANGE TO TIP	60 FT.
NATURAL FREQUENCIES		
FLATWISE	1.50 Hz -1.85 Hz	1.66 Hz
EDGEWISE	2.15 Hz -2.55 Hz	2.47 Hz
WEIGHT, MAXIMUM	3,000 LBS.	2,852 LBS.
MAX. GRAVITY MOMENT STA. 40 IN.	47,000 LB-FT	44,400 LB-FT
CHORDWISE C.G. FROM L.E.	32% MAXIMUM	38%*
MAX. TIP DEFLECTION	103 IN.	97 IN. MAXIMUM

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* ACCEPTABLE BY NASA ANALYSIS

TABLE 4
COMPARISON OF PROTOTYPE BLADE COSTS WITH ESTIMATED PRODUCTION BLADE COSTS

	ESTIMATED COSTS PRODUCTION BLADES			ESTIMATED COSTS PROTOTYPE BLADES		
NUMBER OF BLADES/YR.	2	100	1000	2	100	1000
DIRECT LABOR HRS.	201	151	127	2355	785	453
BURDENED LABOR	5025	3775	3175	41729	13900	8022
BURDENED MATERIAL(1)	8383	6275	5295	28823	8602	4964
Total Cost	13408	10050	8470	67552	22501	12986
Fee @ 10%	1341	1005	847	6755	2250	1299
TOTAL PRICE	14749	11055	9317	74307	24751	14285
AMORTIZED TOOLING	34520	690	69	34520	690	69
GRAND TOTAL	49269	11745	9386	108827	25441	14354

(1) Includes Root End Adapter

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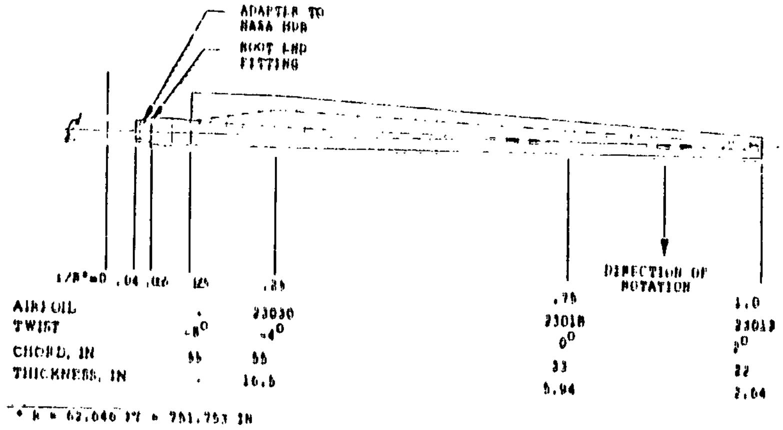
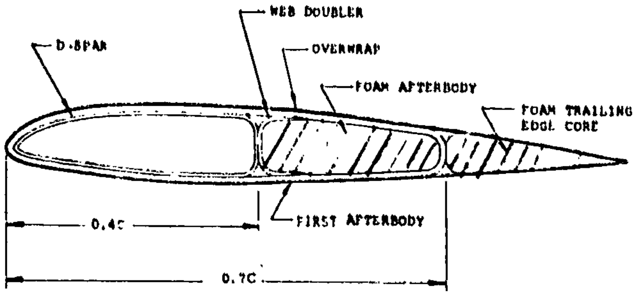


FIGURE 1 BLADE GEOMETRY DEFINITION



STATION .75R

NACA 23018 AIRFOIL

FIGURE 2 TYPICAL BLADE CROSS SECTION

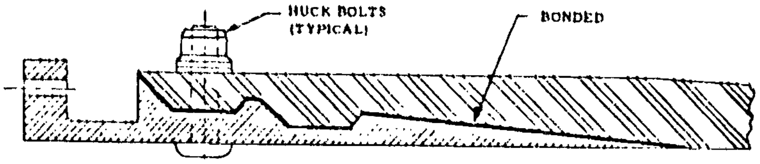


FIGURE 3 ROOT END DETAIL

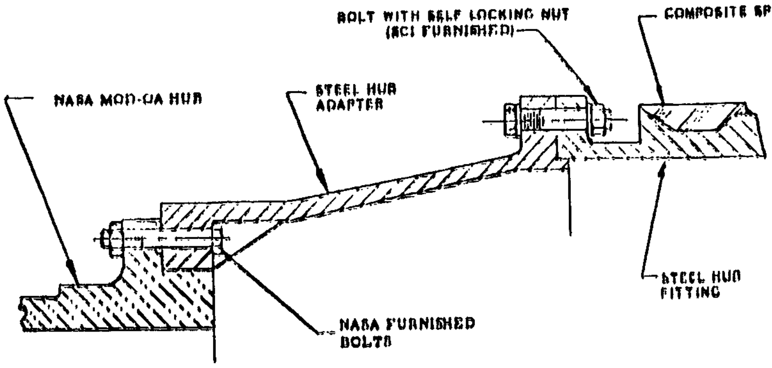


FIGURE 4 HUB ADAPTER DETAILS

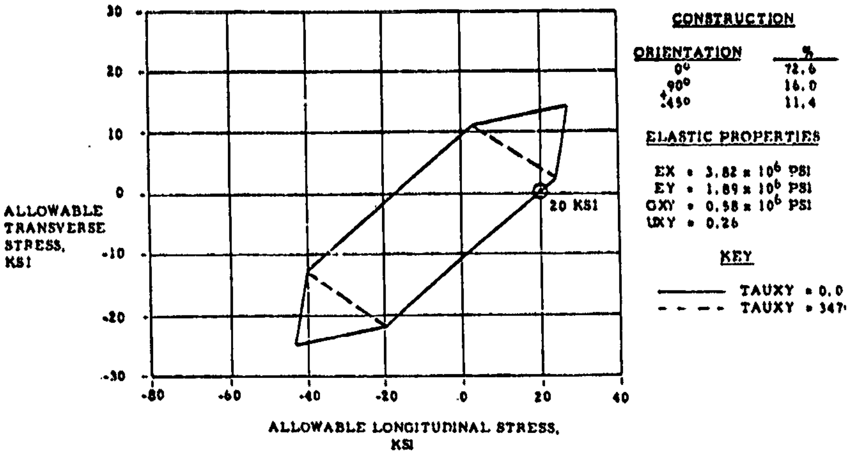


FIGURE 5 COMBINED STRESS ALLOWABLES - TYPICAL SPAR COMPOSITE

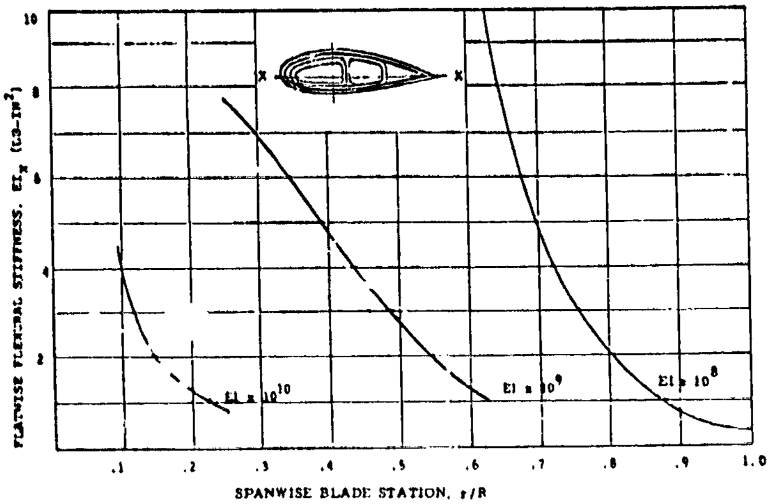


FIGURE 6 BLADE FLATWISE FLEXURAL STIFFNESS

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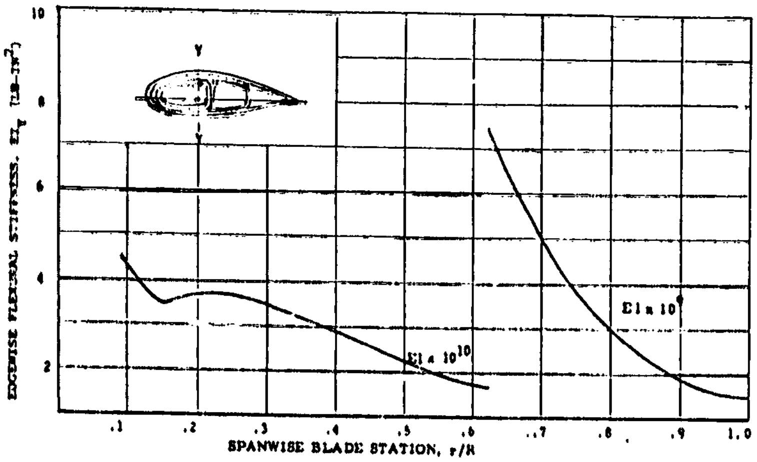
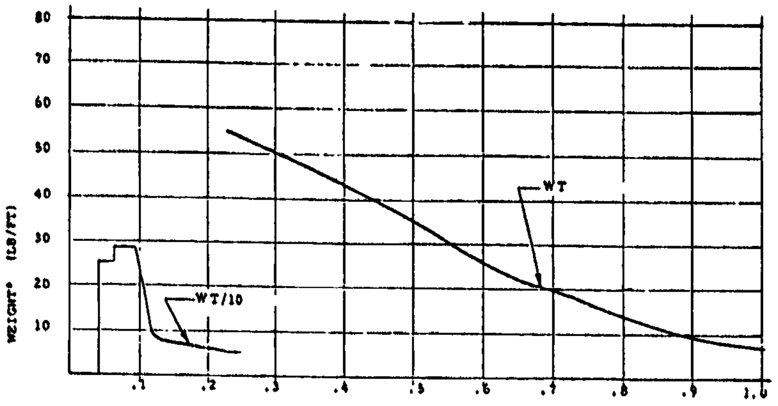


FIGURE 7 BLADE EDGEWISE FLEXURAL STIFFNESS



*Primary Structure and Foam Cores

FIGURE 8 BLADE WEIGHT DISTRIBUTION

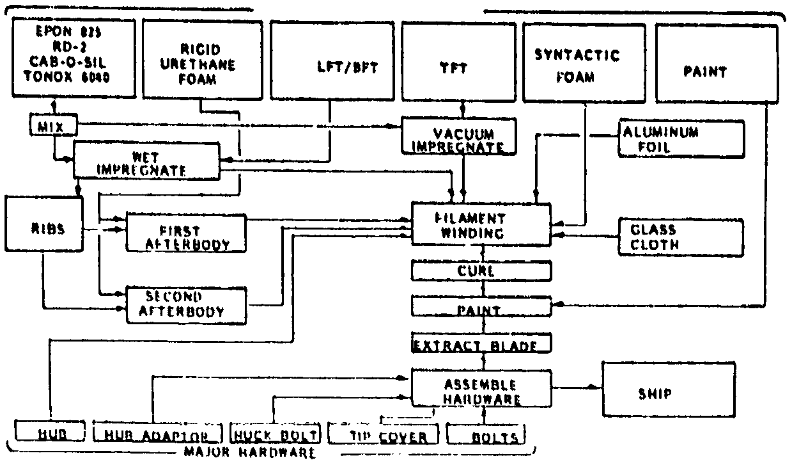


FIGURE 9 FABRICATION PROCEDURE (PROTOTYPE)

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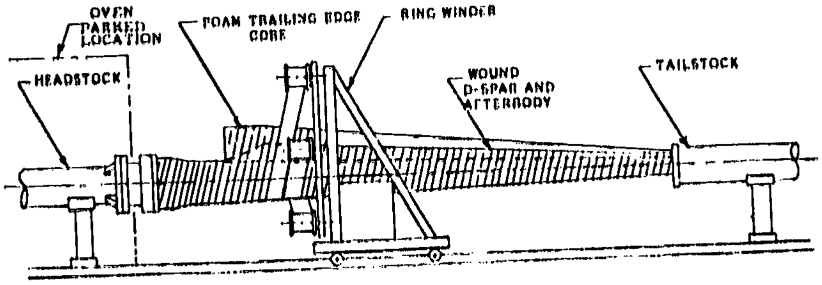


FIGURE 10 MANUFACTURING APPROACH

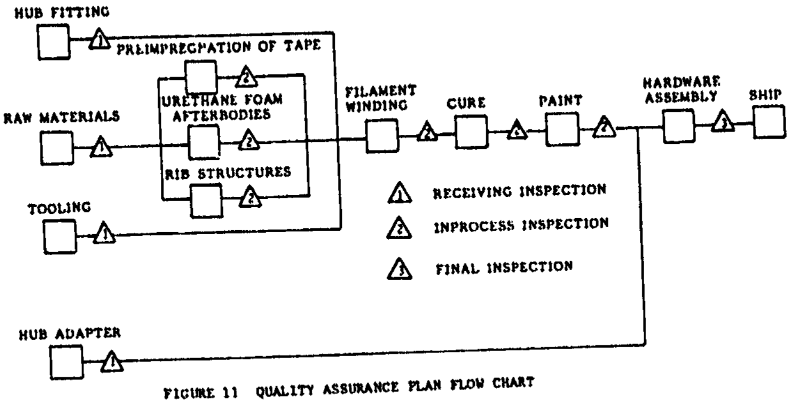
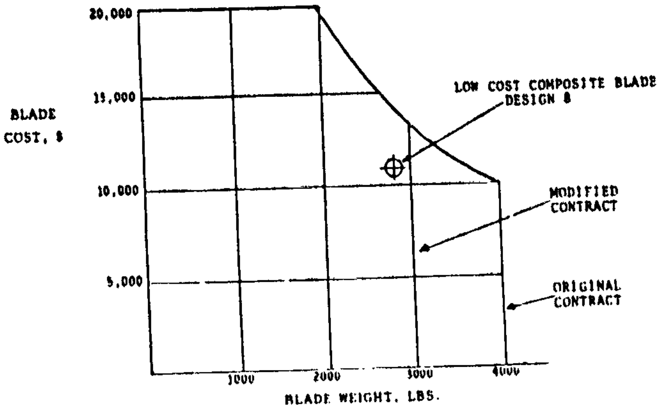


FIGURE 11 QUALITY ASSURANCE PLAN FLOW CHART



(1) 100 BLADES/YEAR, 1978 DOLLARS

FIGURE 12 ALLOWABLE COST/WEIGHT ENVELOPE

QUESTIONS AND ANSWERS

O. Weingart

From: J. Dugundji

Q: How much overlap did you use when winding the 7 inch tape?

A: *3 to $3\frac{1}{8}$ inches. The strength and modulus of the resulting material is comparable to a continuous filament reinforced composite of similar materials, resin, volume, and fiber orientation.*

From: P. A. Bergman

Q: Did you evaluate building a stiffer mandrel to deal with mandrel deflection, rather than the rotating winding system that was built?

A: *No! This was adequately addressed in the Kaman 100 ft blade and Hamilton Standard WTS-4.*